

Resistance of a Rotating-Moving Brane with Background Fields Against Collapse

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Abstract

Using the boundary state formalism we investigate the effect of tachyon condensation process on a rotating and moving Dp -brane with various background fields in the bosonic string theory. The rotation and motion are inside the brane volume. We demonstrate that some specific rotations and/or motions can preserve the brane from instability and collapse.

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1 Introduction

Some significant steps have been made to study the D-branes as essential objects in the string theory and some of their specifications such as stability [1, 2]. The instability of the branes can be studied by the open string tachyon dynamics and tachyon condensation phenomenon [3]. The unstable D-branes decay into the closed string vacuum or to some lower dimensional unstable branes as intermediate states [4, 5, 6]. These intermediate states also decay to lower dimensional stable configurations or to the closed string vacuum. These concepts have been studied by various methods, e.g. the string field theory [4, 7, 8].

On the other hand, there is the boundary state method for describing D-branes [9] - [16]. This method is an applicable tool in many complicated situations. Thus, this valuable formalism can be applied for investigating the tachyon condensation process [17] - [20]. For example, the boundary state is a source for closed strings, therefore, by using this state and the tachyon condensation, one can find the time evolution of the source. In addition, it has been argued that the boundary state description of the rolling tachyon is valid during the finite time which is determined by the string coupling, and the energy of the system could be dissipated to the bulk beyond this time [19]. Besides, this method elucidates the decoupling of the open string modes at the non-perturbative minima of the tachyon potential [21].

In this article we consider a rotating and moving Dp -brane in the presence of a $U(1)$ gauge potential in the worldvolume of the brane and a tachyon field. The rotation and linear motion of the brane will be considered in its volume. Presence of the above background fields indicates some preferred alignments within the brane. Thus, we shall demonstrate that the Lorentz symmetry on the worldvolume of the brane has been broken, and hence such rotations and motions are sensible. The boundary state corresponding to this non-stationary Dp -brane enables us to investigate the tachyon condensation for gaining a new understanding of this phenomenon on the D-branes. In fact, we shall observe that condensation of tachyon cannot always impel the brane to be unstable. In other words, by considering a rotating-moving brane, the reduction of the brane dimension sometimes does not occur, and hence in spite of the tachyon condensation process we have a stable brane.

This paper is organized as follows. In Sec. 2, the boundary state corresponding to a dynamical Dp -brane with various background fields (in the context of the bosonic string

theory) will be constructed. In Sec. 3, stability of this D-brane under the condensation of the tachyon will be investigated. Section 4 is devoted to the conclusions.

2 The boundary state of the brane

As we know open strings live on the D-branes. This elucidates that the corresponding fields of the open string states, such as the gauge potential $A_\alpha(X)$ and the tachyon field $T(X)$, exist on the worldvolume of a Dp -brane. Since the boundary of the emitted (absorbed) closed string worldsheet sits on the brane, the closed string possesses some interactions with the open string fields. In other words, the open string fields naturally behave as backgrounds for any closed string which is emitted (absorbed) by the brane. However, in various papers the open string fields $A_\alpha(X)$ and $T(X)$ have been extremely applied as valuable backgrounds for studying the closed strings, e.g. see Refs. [4, 8, 16, 17, 18, 19, 20, 21, 23, 24].

For constructing the boundary state associated with a non-stationary Dp -brane in the presence of the above background fields, we start with the action

$$S = - \frac{1}{4\pi\alpha'} \int_{\Sigma} d^2\sigma \sqrt{-h} h^{ab} g_{\mu\nu} \partial_a X^\mu \partial_b X^\nu + \frac{1}{2\pi\alpha'} \int_{\partial\Sigma} d\sigma \left(A_\alpha \partial_\sigma X^\alpha + 2\omega_{\alpha\beta} X^\alpha \partial_\tau X^\beta + T(X^\alpha) \right), \quad (1)$$

where Σ is a closed string worldsheet, emitted (absorbed) by the brane, and $\partial\Sigma$ is its boundary. The set $\{X^\alpha | \alpha = 0, 1, \dots, p\}$ represents the worldvolume directions and the set $\{X^i | i = p+1, \dots, d-1\}$ indicates the directions perpendicular to it. This action includes the $U(1)$ gauge potential A_α which lives in the brane worldvolume, a tachyonic field $T(X)$ and a dynamical term. This term has the spacetime angular velocity $\omega_{\alpha\beta}$ for the brane rotation and motion in its volume. The components $\{\omega_{0\bar{\alpha}} | \bar{\alpha} = 1, \dots, p\}$ specify the speed of the brane and the elements $\{\omega_{\bar{\alpha}\bar{\beta}} | \bar{\alpha}, \bar{\beta} = 1, \dots, p\}$ show its rotation.

Unlike the closed string tachyon and dilaton backgrounds which appear in the bulk of the string action and, because of their couplings with the two-dimensional curvature, break the Weyl symmetry our tachyon belongs to the open string spectrum, hence it specifies a surface term for the string action. Therefore, this tachyon field does not couple to the two-dimensional curvature. This fact enables us to choose the flat gauge for the worldsheet metric, e.g. see Ref. [4, 8, 19, 24, 25]. However, beside this choice, for simplification of

the calculations the spacetime metric is chosen as $g_{\mu\nu} = \eta_{\mu\nu} = \text{diag}(-1, 1, \dots, 1)$, and for the gauge potential we use the gauge $A_\alpha = -\frac{1}{2}F_{\alpha\beta}X^\beta$ where the field strength $F_{\alpha\beta}$ is constant. Furthermore, we apply the following tachyon profile $T = T_0 + \frac{1}{2}U_{\alpha\beta}X^\alpha X^\beta$ where T_0 and the symmetric matrix $U_{\alpha\beta}$ are constant.

Note that the second term of the action in the elected gauge can be written as $\frac{1}{4}F_{\alpha\beta}J_\sigma^{\alpha\beta}$. Thus, $F_{\alpha\beta}$ comes from the brane, i.e. electric and magnetic fields on the brane, while $J_\sigma^{\alpha\beta}$ belongs to the closed string. The third term of the action, which possesses the feature $\omega_{\alpha\beta}J_\tau^{\alpha\beta}$, is an analog of the second one, i.e. $\omega_{\alpha\beta}$ is an effect of the brane while $J_\tau^{\alpha\beta}$ pertains to the closed string.

The action gives the following boundary state equations

$$\begin{aligned} (M_{\alpha\beta}\partial_\tau X^\beta + F_{\alpha\beta}\partial_\sigma X^\beta + U_{\alpha\beta}X^\beta)_{\tau=0}|B\rangle &= 0, \\ (\delta X^i)_{\tau=0}|B\rangle &= 0, \end{aligned} \tag{2}$$

where $M_{\alpha\beta} = \eta_{\alpha\beta} + 4\omega_{\alpha\beta}$.

Now we prove that the background fields break the Lorentz invariance along the world-volume of the brane. The action of the Lorentz generators on the boundary state can be extracted from Eq. (2),

$$\begin{aligned} J^{\alpha\beta}|B\rangle &= \int_0^\pi d\sigma \left[(M^{-1}F)^\alpha{}_\gamma X^\beta \partial_\sigma X^\gamma - (M^{-1}F)^\beta{}_\gamma X^\alpha \partial_\sigma X^\gamma \right. \\ &\quad \left. + (M^{-1}U)^\alpha{}_\gamma X^\beta X^\gamma - (M^{-1}U)^\beta{}_\gamma X^\alpha X^\gamma \right]_{\tau=0} |B\rangle. \end{aligned} \tag{3}$$

This equation elaborates that for restoring the Lorentz symmetry the tachyon matrix $U_{\alpha\beta}$ and the field strength $F_{\alpha\beta}$ should vanish. We observe that even in the absence of the electromagnetic fields, the tachyon field independently breaks the Lorentz invariance along the brane worldvolume. However, since the right-hand-side of Eq. (3) is a functional of the spacetime coordinates along the brane worldvolume we deduce that the Lorentz symmetry breaking is local. That is, the linear motion of the brane in any direction obviously is sensible. The same also is true for its rotation. For obtaining more perception of rotation and motion of a Dp -brane in its volume, beside the Lorentz invariance breaking, we should reminisce that such configurations accurately are T-dual of some imaginable systems. More precisely, a rotating-moving Dp -brane can also be constructed via T-duality from a $D(p-1)$ -brane which rotates and moves perpendicular and parallel to its volume. For example, consider a D1-brane along the x^1 -direction with the velocity components V^1 and

V^2 in the directions x^1 and x^2 , respectively. Now apply the T-duality in the x^2 -direction that we assume it is compact. The resulted system represents a D2-brane along the x^1x^2 -plane with the velocity V^1 in the x^1 -direction and possesses an electric field $E = V^2$ in the x^2 -direction. Similarly, it is possible to recast a rotating D2-brane via the T-duality from another setup of the D1-brane. Note that after accomplishing the T-duality effects one can decompactify all compact coordinates.

The other interpretation of Eq. (3) is as follows. The tensor operator $J^{\alpha\beta}$ defines angular momentum of the closed string state $|B\rangle$ along the brane worldvolume. According to the action (1) since the closed string couples to the background fields and spacetime angular velocity of the brane, its angular momentum also is affected by these variables, as expected.

In terms of the closed string oscillators Eqs. (2) find the feature

$$\begin{aligned} & \left[\left(M_{\alpha\beta} - F_{\alpha\beta} + \frac{i}{2m} U_{\alpha\beta} \right) \alpha_m^\beta + \left(M_{\alpha\beta} + F_{\alpha\beta} - \frac{i}{2m} U_{\alpha\beta} \right) \tilde{\alpha}_{-m}^\beta \right] |B\rangle^{(\text{osc})} = 0, \\ & (2\alpha' M_{\alpha\beta} p^\beta + U_{\alpha\beta} x^\beta) |B\rangle^{(0)} = 0, \\ & (\alpha_m^i - \tilde{\alpha}_{-m}^i) |B\rangle^{(\text{osc})} = 0, \\ & (x^i - y^i) |B\rangle^{(0)} = 0, \end{aligned} \quad (4)$$

where the transverse vector $\{y^i | i = p+1, \dots, d-1\}$ defines the location of the brane. The boundary state is given by the direct product $|B\rangle = |B\rangle^{(0)} \otimes |B\rangle^{(\text{osc})}$.

The solution of the zero mode part of the boundary state is given by

$$\begin{aligned} |B\rangle^{(0)} &= \frac{1}{\sqrt{\det(U/2)}} \int_{-\infty}^{\infty} \exp \left\{ i\alpha' \left[\sum_{\alpha=0}^p (U^{-1}M)_{\alpha\alpha} (p^\alpha)^2 \right. \right. \\ &+ \left. \left. \sum_{\alpha,\beta=0,\alpha\neq\beta}^p (U^{-1}M + M^T U^{-1})_{\alpha\beta} p^\alpha p^\beta \right] \right\} \left(\prod_{\alpha} |p^\alpha\rangle dp^\alpha \right) \otimes \prod_i \delta(x^i - y^i) |p^i = 0\rangle \end{aligned} \quad (5)$$

The factor $1/\sqrt{\det(U/2)}$ is induced by the disk partition function [22]. The exponential factor of this state, which is absent in the conventional boundary states, originates from the tachyon field. For the oscillating part the coherent state method imposes the following solution

$$|B\rangle^{(\text{osc})} = \frac{T_p}{g_s} \prod_{n=1}^{\infty} [\det Q_{(n)}]^{-1} \exp \left[- \sum_{m=1}^{\infty} \frac{1}{m} \alpha_{-m}^\mu S_{(m)\mu\nu} \tilde{\alpha}_{-m}^\nu \right] |0\rangle, \quad (6)$$

where the matrices have the following definitions

$$Q_{(m)\alpha\beta} = M_{\alpha\beta} - F_{\alpha\beta} + \frac{i}{2m} U_{\alpha\beta},$$

$$\begin{aligned}
S_{(m)\mu\nu} &= \left(\Delta_{(m)\alpha\beta} , -\delta_{ij} \right) , \\
\Delta_{(m)\alpha\beta} &= (Q_{(m)}^{-1} N_{(m)})_{\alpha\beta} , \\
N_{(m)\alpha\beta} &= M_{\alpha\beta} + F_{\alpha\beta} - \frac{i}{2m} U_{\alpha\beta} .
\end{aligned} \tag{7}$$

The mode dependency of these matrices is induced by the tachyon matrix. The normalization factor $\prod_{n=1}^{\infty} [\det Q_{(n)\alpha\beta}]^{-1}$ is inspired by the disk partition function [22]. The zeta function regulation gives $\sum_{n=1}^{\infty} 1 \rightarrow -1/2$, and hence $\prod_{n=1}^{\infty} \det U^{-1} \rightarrow \sqrt{\det U}$. Therefore, for the total prefactor of the boundary state we acquire

$$\frac{\prod_{n=1}^{\infty} [\det Q_{(n)}]^{-1}}{\sqrt{\det(U/2)}} \longrightarrow 2^{(p+1)/2} \prod_{n=1}^{\infty} \det \left[(M - F)U^{-1} + \frac{i}{2n} \mathbf{1} \right]^{-1} . \tag{8}$$

According to the first equation of (4), on the boundary state one can express the right-moving oscillator α_m^α in terms of all left-moving oscillators $\{\tilde{\alpha}_{-m}^\beta | \beta = 0, 1, \dots, p\}$, which causes the matrix $\Delta_{(m)\alpha\beta}$ to appear in the boundary state. If we express $\tilde{\alpha}_m^\alpha$ in terms of the set $\{\alpha_{-m}^\beta | \beta = 0, 1, \dots, p\}$, the boundary state possesses the matrix $\left([\Delta_{(-m)}^{-1}]^T \right)_{\alpha\beta}$. Equality of these matrices gives the condition $\Delta_{(m)} \Delta_{(-m)}^T = \mathbf{1}$. Since this equation comprises all mode numbers of the closed string it splits to the following conditions

$$\begin{aligned}
\eta U - U \eta + 4(\omega U + U \omega) &= 0, \\
\eta F - F \eta + 4(\omega F + F \omega) &= 0,
\end{aligned} \tag{9}$$

which are independent of the mode numbers. These equations reduce $(p+1)(3p+2)/2$ parameters of the theory to $p(p+1)/2$.

In fact, the total boundary state contains a portion of the conformal ghosts too. Since this part does not include the background fields it will not contribute to the tachyon condensation. Thus, in the future discussions we shall neglect it.

3 Tachyon condensation and brane stability

Study of the open string tachyon field which began basically by the Sen's papers [3] demonstrates that this tachyon field has an essential role on improving our knowledge about the fate of the D-branes, their instability or stability, true vacuum of the tachyonic string theories and so on. In fact, the tachyonic modes of the string spectrum make the D-branes to be unstable [3]. As the tachyon condenses the dimension of the brane

decreases and in the final stage only the closed string degrees of freedom remain. From the boundary sigma-model point of view, in the d -dimensional spacetime the tachyon condensation starts by a conformal theory with the d Neumann boundary conditions in the UV fixed point. Then adding the tachyon as a perturbation (deformation) will cause the theory to roll toward an IR fixed point. Afterwards we receive a closed string vacuum with a Dp -brane, which corresponds to a new vacuum with $(d - p - 1)$ Dirichlet boundary conditions.

Since the boundary state represents a brane in terms of the quantum states of closed string and contains the disk partition function as the normalization factor, it is an appropriate tool for evaluating the behavior of a Dp -brane under the tachyon condensation process. Therefore, by applying this formalism, in this section we shall demonstrate that for a dynamical brane, some rotations and/or motions can prevent the brane from instability and collapse. This is different from the conventional tachyon condensation which reduces the brane dimension.

For making the tachyon condensation, some of the tachyon's components (at least one of them) should go to infinity. In Eqs. (5) and (6) there are the matrices $L = U^{-1}M + M^T U^{-1}$, $(U^{-1}M)_{\alpha\alpha}$ which is diagonal, $\Delta_{(m)}$, and also the prefactor in the right-hand side of Eq. (8) in which the tachyon matrix $U_{\alpha\beta}$ exists. That is, we should take the limits of these variables to obtain the evolution of the Dp -brane under the condensation of the tachyon. Now let the system approach to the infrared fixed point, i.e. $U_{pp} \rightarrow \infty$. This gives the following limit

$$\lim_{U_{pp} \rightarrow \infty} (U^{-1})_{p\alpha} = \lim_{U_{pp} \rightarrow \infty} (U^{-1})_{\alpha p} = 0, \quad \alpha = 0, 1, \dots, p. \quad (10)$$

The Eq. (10) induces the following limit on the elements of the diagonal matrix

$$(U^{-1}M)_{\alpha\alpha} = (U^{-1})_{\alpha\gamma'} M^{\gamma'}_{\alpha} + (U^{-1})_{\alpha p} M^p_{\alpha} \longrightarrow (U^{-1})_{\alpha\gamma'} M^{\gamma'}_{\alpha}, \quad \gamma' \in \{0, 1, \dots, p-1\}. \quad (11)$$

Thus, the element $(U^{-1}M)_{pp}$ vanishes, and the diagonal matrix $(U^{-1}M)_{\alpha\alpha}$ reduces to a $p \times p$ diagonal matrix $(U^{-1})_{\alpha'\gamma'} M^{\gamma'}_{\alpha'}$ with $\alpha', \gamma' \neq p$. In fact, this diagonal matrix is not a main portion of the boundary state. Hence reduction of it to a $p \times p$ matrix is ignorable. We shall see that all other matrices, in the infrared fixed point, remain $(p+1) \times (p+1)$.

The matrix elements $L_{\alpha\beta}|_{\alpha \neq \beta}$ have the limit

$$L_{\alpha\beta} = (U^{-1})_{\alpha\gamma'} M^{\gamma'}_{\beta} + (M^T)_{\alpha}^{\gamma'} (U^{-1})_{\gamma'\beta}, \quad \alpha \neq \beta. \quad (12)$$

Therefore, in this limit the elements $L_{\alpha'p} = L_{p\alpha'} = 4(U^{-1})_{\alpha'}{}^{\gamma'} \omega_{\gamma'p}$ are nonzero unless the case $\{\omega_{\gamma'p} = 0 \mid \gamma' = 0, 1, \dots, p-1\}$. Since ω_{0p} is corresponding to the velocity of the brane along the x^p -direction and $\omega_{\gamma'p}|_{\gamma' \neq 0,p}$ associated with the brane rotation inside the $x^{\gamma'}x^p$ -plane we observe that these components of the motion and rotation preserve this portion of the boundary state against dimensional reduction. This also elaborates that the other components of the rotation and motion, i.e. $\{\omega_{\alpha'\beta'}|_{\alpha',\beta' = 0, 1, \dots, p-1}\}$, do not preserve this portion of the boundary state against collapse. We shall observe that the dimensional preserving also occurs for the other parts of the boundary state via the same components of the rotation and motion.

The prefactor of the boundary state, i.e. the right-hand side of Eq. (8), under the limit $U_{pp} \rightarrow \infty$, takes the feature

$$2^{(p+1)/2} \prod_{n=1}^{\infty} \det \left[(M - F) \tilde{U}^{-1} + \frac{i}{2n} \mathbf{1} \right]^{-1}. \quad (13)$$

According to Eq. (10) the matrix \tilde{U}^{-1} is similar to U^{-1} where its last row and its last column possess zero matrix elements. This implies that the last column of the matrix $(M - F) \tilde{U}^{-1}$ vanishes while its last row has the nonzero elements $(4\omega - F)_p{}^{\gamma'} (\tilde{U}^{-1})_{\gamma'\beta}$. That is, after the process of the tachyon condensation the normalization factor of the boundary state also respects the totality of the Dp -brane.

Now the matrix $\Delta_{(m)\alpha\beta}$ is investigated. In the limit $U_{pp} \rightarrow \infty$ the last row of this matrix vanishes except the element $\Delta_{(m)pp}$ which tends to -1 . The elements of the last column, which are $(\Delta_{(m)})_{\alpha'p}|_{\alpha' \neq p}$, remain nonzero if $\{\omega_{\alpha'p} \neq 0 \mid \alpha' = 0, 1, \dots, p-1\}$. Thus, this part of the boundary state also resists against dimensional reduction of the brane.

Adding all these together we observe that the rotation of the brane in the planes $\{x^{\bar{\alpha}}x^p \mid \bar{\alpha} = 1, 2, \dots, p-1\}$ and/or its motion along the direction x^p induce a resistance against the instability and collapse of the brane. However, the other components of the brane dynamics do not preserve it.

Example: the D2-brane

For illustrating the stability of a non-stationary brane under the tachyon condensation phenomenon consider the simplest example, i.e. the D2-brane. The tachyon condensation is applied by the limit $U_{22} \rightarrow \infty$. Therefore, according to Eq. (13) the dimension of the matrices in the total prefactor remains 3×3 . Besides, the matrix elements L_{02} and L_{12}

don't vanish. In addition, we obtain

$$\lim_{U_{pp} \rightarrow \infty} \Delta_{(m)} = \begin{pmatrix} \Delta_{(m)00} & \Delta_{(m)01} & \Delta_{(m)02} \\ \Delta_{(m)10} & \Delta_{(m)11} & \Delta_{(m)12} \\ 0 & 0 & -1 \end{pmatrix}, \quad (14)$$

where

$$\Delta_{(m)02} = \frac{-8\omega_{12}(4\omega_{01} - F_{01} + \frac{iU_{01}}{2m}) + 8\omega_{02}(1 + \frac{iU_{11}}{2m})}{(-1 + \frac{iU_{00}}{2m})(1 + \frac{iU_{11}}{2m}) + (4\omega_{01} - F_{01})^2 + (\frac{U_{01}}{2m})^2},$$

$$\Delta_{(m)12} = \frac{-8\omega_{02}(-4\omega_{01} + F_{01} + \frac{iU_{01}}{2m}) + 8\omega_{12}(-1 + \frac{iU_{00}}{2m})}{(-1 + \frac{iU_{00}}{2m})(1 + \frac{iU_{11}}{2m}) + (4\omega_{01} - F_{01})^2 + (\frac{U_{01}}{2m})^2}.$$

All the above facts elucidate that motion of the brane along the x^2 -direction and/or its rotation in the x^1x^2 -plane preserve it against instability. We observe that motion of the brane along the x^1 -direction does not have this ability.

4 Conclusions and outlook

We studied effects of tachyon condensation on a rotating-moving Dp -brane with the $U(1)$ gauge potential and the quadratic tachyon field via the boundary state method in the bosonic string theory. The conventional tachyon condensation usually is terminated by reduction of the brane dimension. In this article we observed that special rotations and/or special motions of the brane can protect it from instability and hence dimensional reduction. As it was proved, because of some components of the linear velocity and angular velocity of the brane, at the infrared fixed point it resists against the instability and collapse. More precisely, this dynamics of the brane imposes a solitonic behavior to it. However, the other rotations and motions of the brane in its volume do not preserve it.

It is valuable and interesting to extend the setup of this article to the transverse linear motion and a rotation in which one of the brane directions to be axis of rotation. Besides, the extension can be done for the BPS and non-BPS D-branes in the superstring theory for the tangential rotation and motion, and also for the transverse rotation and motion through the boundary state formalism.

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